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13. ABSTRACT *(Maximum 200 Words)*
This research project is concerned with displays for digital mammography. A demountable display tube with its associated vacuum system and electronic control was acquired. It permits investigation of samples of novel cathodo-luminescent materials and their respective substrates with respect to characteristic display performance measures.

Work concentrated on CsI as the luminescent material. CsI grows in a fiber like structure, which suggests little lateral light propagation, which could result in high image contrast. CsI samples of different thickness were obtained. The luminescence developed by CsI at 7kV beam electrons is linearly proportional to the beam current and almost linearly proportional to the thickness of the sample. This very important observation suggests that perhaps effects other than just simple cathodo-luminescence affect the generation of light when CsI is used as phosphor in a CRT. It is hypothesized that the increased luminance is the result of injected beam electrons causing electro-luminescence. These electrons can acquire sufficient energy to cause impact excitation of thallium centers along the length of CsI columns.

This important result suggests a means of overcoming a serious deficiency in CRTs, namely inefficient cathodo-luminescence and low luminance levels compared to that from the film-light box used in diagnostic radiology

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FOREWORD

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Haven Rodriguez 07/15/00

PI - Signature Date

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Introduction

This research project is concerned with digital mammography, the thrust of which is to improve on diagnostic performance using a digital detector and an electronic display instead of the "state of the art" radiographic film-screen detector and the film-light box. An essential component of this digital system is the display from which diagnosis is to be carried out. CRTs are the maturest displays at this time. They have already become an integral part of the diagnostic radiology department. Primary diagnosis by the radiologist using high performance CRTs is being explored in various radiological categories [1]. In fact the US Armed Forces have accelerated the proliferation of digital imaging methods including primary diagnosis using softcopy displays through the Medical Diagnostic Imaging Support (MDIS) program [2] and many Universities are following suit [3]. Initial results appear to be encouraging, even though serious questions remain. A recent workshop on problems of softcopy displays for use in digital mammography, organized by the Office of Women's Health [4] testifies that the medical community as well as the Federal Government is focussing its attention on the problem of finding adequate softcopy displays for primary diagnosis. Problems addressed during this workshop included optimization of the display-observer interface and standardization.

CRT displays have been undergoing intense development over the past 10-15 years and research on new display devices as well as development of new display devices is underway. Research programs at the University of Arizona concentrate on quantitative measures of display performance. These programs have led to the realization that CRT performance is far from ideal:

- The luminance is lower than that of the film-light box because of low efficiency of the phosphor.
- Contrast is low because of scatter within the phosphor particles and off and within glass surfaces.
- Spatial resolution at high luminance depends on the diameter of the electron beam.

Significant improvement is unlikely if the traditional CRT structure, the faceplate and the deposition of the granular phosphor in a binder on this faceplate, is not changed. It is the objective of this research project to investigate means to improve phosphors for softcopy displays.

CsI might be a good candidate to replace the powder phosphor as the luminescent material. CsI grows in a fiber like structure, which suggests little lateral light propagation, an important characteristic in view of high image contrast. It is widely used in x-ray image detectors such as x-ray image intensifiers. Fig. 1 is an electron-microscope image of CsI, showing very clearly the columns.

Body

A. Problems encountered during the project

Unfortunately, this project was marred by a variety of major and unusual problems, which caused significant delays in the planned research:

- First the manufacturer of the demountable display tube, Teltron Inc. of Birdsboro, PA, was 4 to 5 months late with the delivery of the system.
- Then the demountable display system did not work and needed to be returned to the manufacturer several times.
- In the second year the supplier of the CsI samples, University of California at Berkely, developed severe difficulties with the purity of CsI to be evaporated on the glass substrates. In fact we could not get any more samples than the three which we got in the first year. This despite the fact, that the University of California at Berkely is a well known and well respected supplier of CsI, who is also known to be reliable.

As a result of the problem with CsI samples, we searched for a new supplier and were relatively successful. The new supplier is Radiation Monitoring Devices (RMD) of Watertown MA. Unfortunately there is still a problem: since we depleted our funds, we have to rely on samples which are made when the production schedule of RMD meets our requests.

It is to be noted however, that despite the general lack of samples, those few samples, which we received, permitted us to determine that CsI has the ability to combine cathodo-luminescence and electro-luminescence, providing essentially a gain over the luminescence from cathodo-luminescence alone. This observation has never been described. This observation caused Dr. Sol Nudelman to make a theoretical study, which was included in the 1999 annual report.

B. Instrumentation and methods

A demountable display station was acquired. Fig. 2 shows schematically the heart of this system, the demountable display tube. The objective of this demountable display station was to permit analysis of pertinent image quality parameters of a variety of luminescent samples, predominantly CsI. This display station is described in great detail below.

CsI samples with different thickness were acquired from different vendors. All samples were 3" in diameter. The luminance of the samples was measured with a hand held photometer while a uniform field was displayed ("written") on the phosphor sample with the scanning electron beam. The image quality of the samples was analyzed with a CCD camera in taking an image while a test pattern such as an SMPTE [5] pattern was displayed by ("written on") the CsI sample.

When it was realized that CsI has the ability to combine cathodo-luminescence and electro-luminescence, a system was built, that permits observing two luminescence effects simultaneously, namely x-ray induced photo-luminescence and electro-luminescence. Such a

system would permit in depth study of these gain mechanisms much easier than the demountable display system, which always has the problem of the need for vacuum and always will suffer from the deterioration of the cathode of the electron gun. It is shown in Fig. 3 a and b and is discussed in more detail below.

1. The Demountable Display Tube

The demountable display tube is basically a CRT with an electron gun, a scanning electron beam and an electrical input to modulate the electron beam with a video signal. It differs from the conventional CRT in that it does not have a permanent vacuum, rather it has a vacuum pump, which can be turned off to let the pressure rise to atmospheric level, remove the front cover and remove the phosphor in order to replace it with another one.

The particular features of the demountable display station are discussed with reference to Fig. 4. through Fig. 7.

Fig. 4 shows a demountable display tube on the upper right and a sealed off display tube on the upper left. This photograph also shows 2 CsI samples on glass substrates in plastic bags (lower left). Seen are also the metal rings, which hold the phosphor samples in the demountable tube.

Fig. 5 is a photograph of the overall system. It shows the essential parts, like the demountable tube (center), the vacuum system (upper left), the control box (upper right) and the CCD camera (lower right).

It is crucial for the operation and particularly for the lifetime of the electron gun, that the thermionic cathode of the electron gun is not exposed to air during the change of luminescent samples. Filling the electron gun section of the tube with an inert gas such as nitrogen (N_2) during the change of the samples avoids catastrophic reduction of electron emission. The hose feeding the nitrogen into the vacuum chamber is visible in the upper left of Fig. 5. The vacuum system (upper left of Fig. 5) is mainly a turbo-molecular pump, capable of maintaining pressures of close to 10^{-8} Torr.

The control box, visible in the upper right of Fig. 5, and in Fig.6, provides the necessary voltages for the display tube. In particular it features

- Display of a 1024 x 768 line monochrome image on the target. The images are test patterns like the SMPTE pattern [5] and other pertinent test patterns for evaluation of image display systems. These images are stored in a PC, connected to the control box.
- Adjustable anode voltage, focus voltage, image size, image centering, image brightness and image contrast
- Meters for anode voltage and screen current.

Fig. 5 shows also in the lower right part the position of the CCD camera and its lens relative to the display tube. Recall that the CCD camera is used to evaluate the images produced by the various phosphor samples placed into the demountable display system. Actually in this Fig. 5,

the CCD camera is slightly moved off-axis with respect to the display tube in order to see the display tube.

Fig. 7 finally is a photograph of the demountable display tube in operation. The tube displays the SMPTE pattern, using one of the CsI samples as the luminescent phosphors.

2. System to permit analysis of simultaneous occurrences of different types of luminescence: X-ray induced photo-luminescence and electro-luminescence of CsI samples

After the discovery, that CsI did exhibit cathodo-luminescence and simultaneously electroluminescence, it was felt one needed a system to easily study these types of effects. Such a system should permit in depth study of the gain mechanisms associated with the combination of two different luminescence mechanisms such as x-ray induced photo-luminescence and electro-luminescence. It would avoid the difficulties of the demountable display system, namely the problem of the need for vacuum and the deterioration of the cathode of the electron gun

Such a system was built in year three. It is shown in Fig. 3 a and b. It includes a photometer, a sample holder with electrodes to apply an electric field to the CsI sample, and an x-ray source. Power supplies are available to apply AC as well as DC fields with field strengths up to 10^6 v/cm. The photometer views the sample via a 45° mirror in order to avoid direct exposure to x-rays (it uses a Si-diode as sensor and would provide an off-set current due to x-rays). The x-ray source is a standard diagnostic x-ray source and permits generation of x-ray beams from 50 to 110 kVp at currents of up to 1 amp.

Key Research Accomplishments

A. Evaluation of CsI Samples

Three CsI samples with thickness of 10 m, 20 m, and 65 m were obtained from the University of California at Berkeley, while two samples with thickness 30 m, and 135 m came from RMD. All samples were 3" in diameter.

1. The relation between beam current and screen luminance

Of particular interest in evaluating any phosphor sample ("screen") for use in a cathode ray tube is the sensitivity, the relation between beam current and screen luminance. This relation was found by exciting the phosphor samples with uniform video images (the whole field set to the same digital value), and measuring the resulting luminance with a photometer. The value of the beam current was read with the aid of the current meter provided in the control box (see the right red display in Fig. 6).

Fig. 8 is a plot of the luminance as a function of beam current for the 5 CsI samples in comparison with that of the sealed off tube and an experimental screen using a P43 phosphor on a 3" glass plate (identified in Fig. 8 as "P43 sample with Al-backing"). The data obtained with

the 2 CsI samples from RMD are shown in red, while those pertaining to the samples from Berkley are shown in black. Notice that for all samples, the relation between luminance and beam current is linear, as it should be. The sealed off tube has the highest sensitivity: for a beam current of about 12 A, the luminance is about 400 cd/m^2. The sensitivity of the CsI samples is clearly lower than that of the phosphor in the sealed-off display tube. This is not too surprising, because the phosphors in sealed-off tubes have aluminum backing which almost doubles the light output due to reflection. None of the CsI samples however had an aluminum backing for reflection.

Most surprising however is the fact that the sensitivity of the 5 CsI samples appears to be also proportional to the sample thickness. While the 120 m thick sample has the highest light output, namely about 340 cd/m^2 for a beam current of about 12 A, the luminance of the 10 m thick CsI sample for a 12 A beam current is only about 100 cd/m^2.

Fig. 9 is a plot of the current sensitivity in units of (cd/m^2)/(A) as a function of sample thickness. Notice that the light output is almost linear with the sample thickness.

The observation that the luminance is related to the sample thickness suggests that perhaps effects other than just simple cathodo-luminescence affect the generation of light when CsI is used as phosphor in a CRT. It is known that cathodo-luminescence of some phosphors can be enhanced by applying an electric field across the luminescent phosphor [6]. It is also known that CsI shows electro-luminescence [7]. However the combination of cathodo-luminescence and of electro-luminescence in CsI has never been reported. These results are very encouraging. Fig. 10 serves to illustrate how an electric field can build up on account of the high resistivity of CsI, leading to electro-luminescence in addition to cathodo-luminescence. Notice that ultimately it is the combination of a charge build-up and the simple voltage drop, caused by the current flowing through the resistance represented by the CsI sample, which determines the maximum electric field. Notice also that the resistor is not simply the CsI sample disc with its 3" diameter and thickness, but the CsI pixel as formed by the scanning electron beam (approximate diameter 20 to 30 micrometers) and the thickness of the CsI sample. Crude estimates are that field strengths are in the range between 10^4 to 10^6 V/cm, values sufficient for many materials to exhibit electro-luminescence.

It is consistent with the notion of the build-up of an electric field that the luminance increases slowly and reaches its maximum luminance within 2 to 4 min. as seen in Fig. 11.

2. Study of simultaneous occurrences different types of luminescence: X-ray induced photo-luminescence and electro-luminescence of CsI samples

Unfortunately, mainly due to the fact that we had run out of funds and RMD supplied CsI samples to us free of charge, but only in conjunction with CsI depositions for other customers, there was only one opportunity to use this system. Here a CsI sample of approximately 0.035 mm from RMD was used. The sample had an Al-cover on the back to apply the voltage to generate the electrical field for the electro-luminescence. Soon after the application of the AC field of about 800 Vpp it was realized, that the sample wouldn't work. Many black points occurred quickly, associated with light flashes. Apparently the aluminum backing in combination

with the rather thin CsI sample thickness provided many shorts such that an electric field could never build up to sufficiently high magnitude to permit electro-luminescence to occur.

3. Spatial Resolution: Response to a Squarewave Pattern and to the SMPTE Pattern.

In an attempt to get a first idea of contrast transfer, a horizontal square wave pattern of 4 lines on – 4 lines off was written onto the samples. The CCD camera recorded the resulting image and the CCD image was then analyzed using appropriate image analysis software (which was developed in-house). Of interest was the modulation, defined as $M = (max - min)/(max + min)$

Fig. 12 shows the results for the 10 m thick and the 65 m thick samples. Clearly, the modulation is much higher for the 10 m thick sample than that for the 65 m thick sample, which is surprising, knowing that CsI grows in columns and should exhibit little lateral light scatter. However it is also known that lateral light scatter can only be avoided, if the columns do not touch each other. This condition can be met by careful adjustment of the growth conditions. But these conditions could not be met under the circumstances encountered during this research project.

Fig. 13 is a luminance profile across a portion of a thick and a thin CsI sample, scanned by an electron beam to generate cathodo-luminescence. Notice that the lateral scatter is larger for the thick sample than for the thin sample, while inherently it was not expected to encounter any lateral light leakage.

Fig. 14 finally is an image of the SMPTE test pattern. Inspection of the resolution patterns reveals the typical trend in the resolution of CRTs: The resolution in the vertical direction is usually much better than that in the horizontal direction, i.e., horizontal lines can be discerned easier than vertical lines.

Reportable Outcomes

The most important outcome of the research performed under this project is the observation that the luminance for CsI is related to the sample thickness. We have no other explanation than that for CsI cathodo-luminescence is combined with electro-luminescence, which has never been reported for CsI. Such effects should lead to superior materials for use in CRTs. These results are very encouraging and they ought to be published. However one would require more experimental evidence to justify publication in a refereed journal.

There are efforts to use the material to obtain funding for the necessary research as evidenced by the outline of a research proposal in the appendix of the report for the year 1999.

Conclusion

Experimental equipment necessary to investigate novel cathodoluminescent samples has been developed. Performance tests with 5 CsI samples showed encouraging and most unusual results. Most important are those results, which indicate that in CsI, cathodo-luminescence can combine

with video controlled electro-luminescence to yield high luminance output. Such results have never been reported for CsI and perhaps can lead to superior materials used in CRTs. These results are encouraging but by no means conclusive. More work is necessary and is underway. One lingering problem is that measurements on five samples were not able to provide convincing evidence by themselves that the columnar structure of CsI reduced lateral scatter and enhanced contrast. In fact it appears that all samples show substantial lateral scatter. Developments at RMD indicate, that columnar growth of CsI with free standing columns is possible now.

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List of personnel receiving pay from this research effort

The following personnel received pay from this research effort and contributed to this research effort:

Hans Roehrig, Ph.D., Research Professor of Radiology and Optical Sciences, Principal investigator

Mike Arthur, Senior Engineer

Sol Nudelman, Ph.D., Professor of Radiology and Optical Sciences, Consultant

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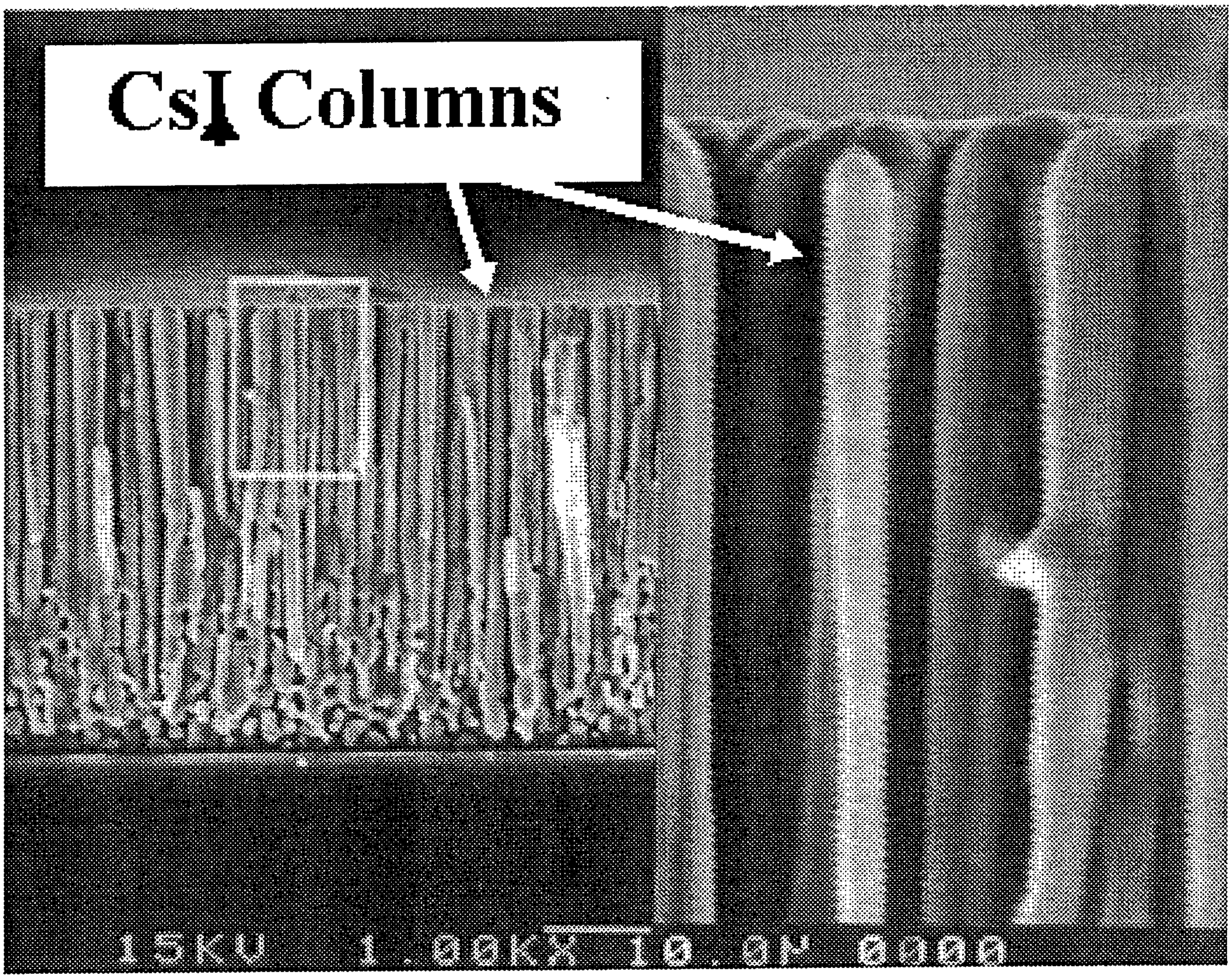

Fig. 1. Electron Microscope of CsI sample showing columnar growth. Notice that some columns are free standing

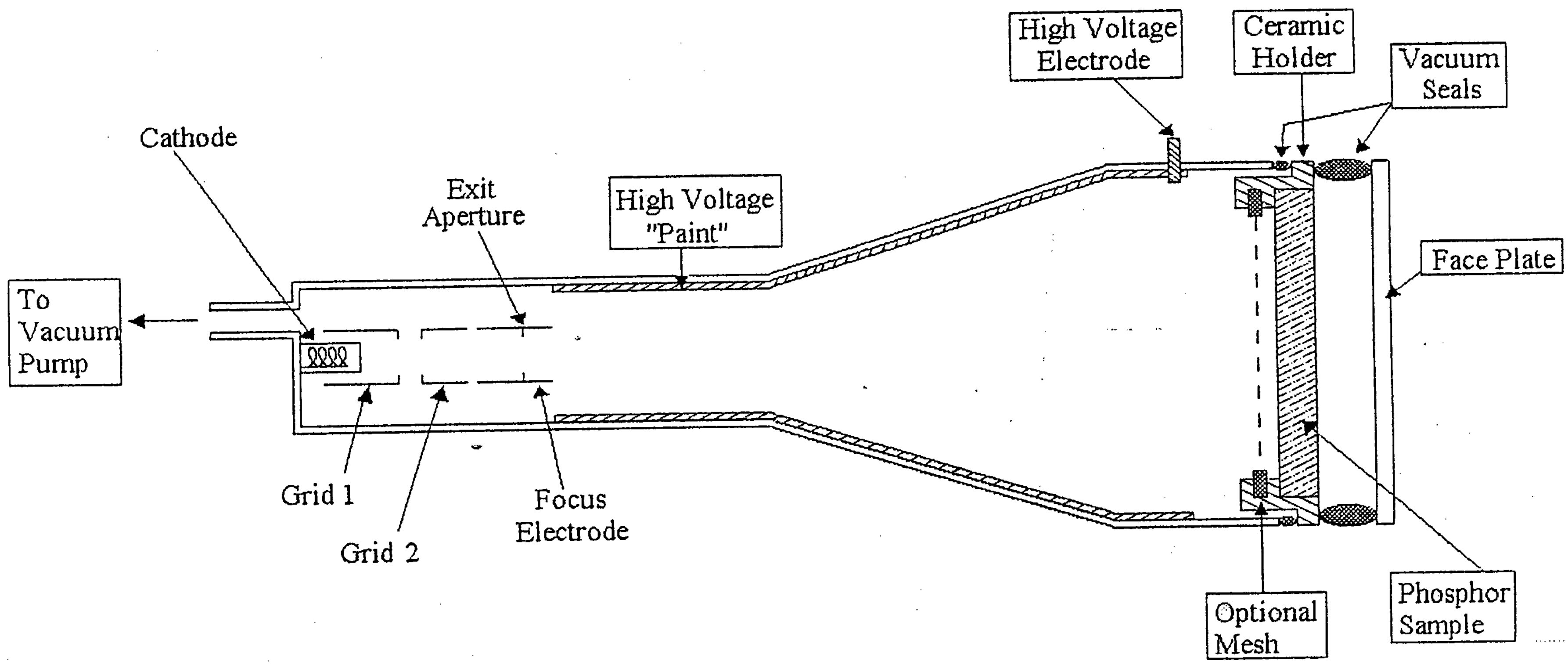

Fig. 2 Schematic of demountable display tube

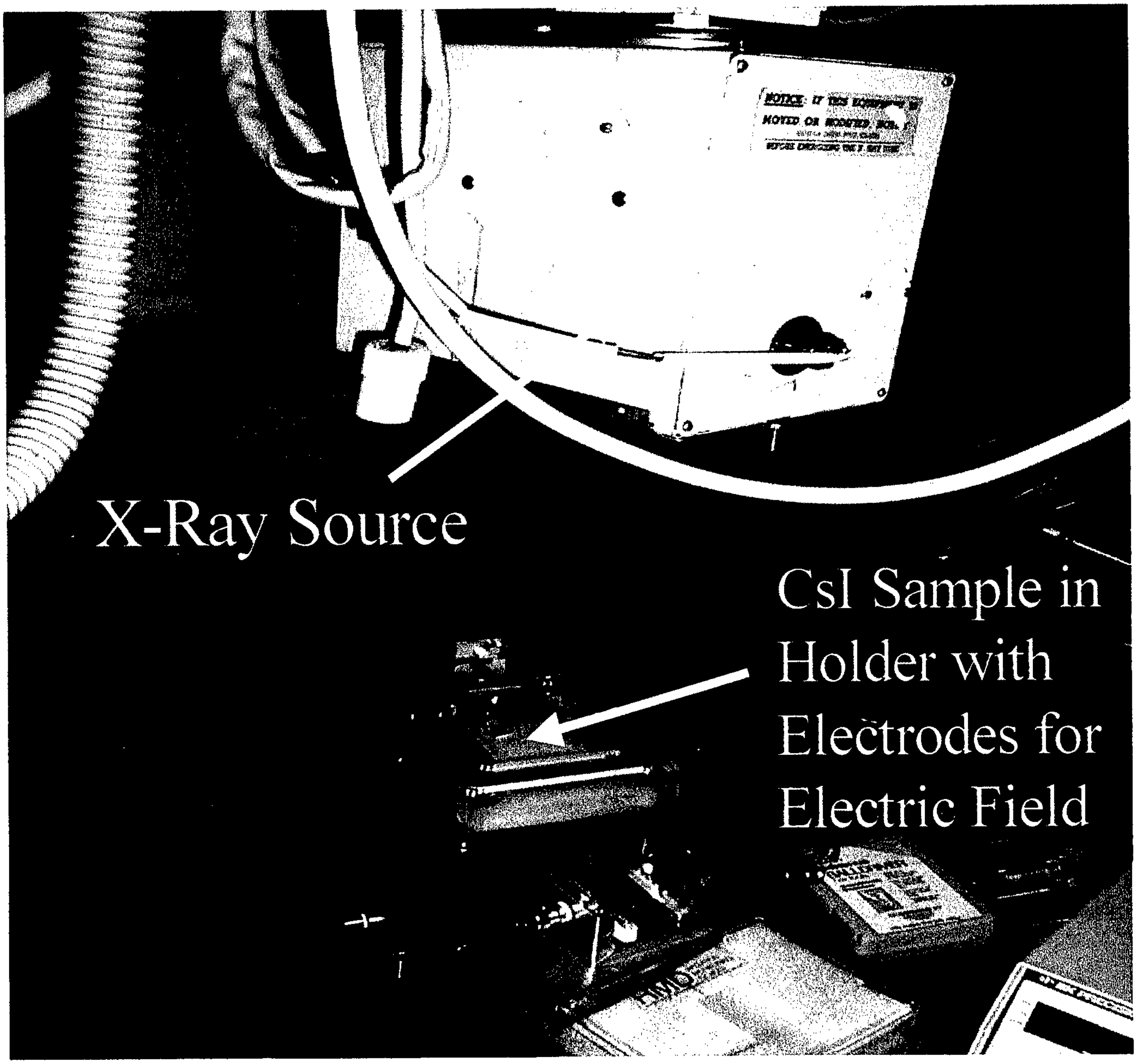

Fig. 3 a. X-ray source and CsI sample holder of the facility to investigate electro luminescence of CsI in conjunction with x-ray induced photo-luminescence of CsI

Fig. 3 b. CsI sample holder and photometer of the facility to investigate electro luminescence of CsI in conjunction with x-ray induced photo-luminescence of CsI

Fig. 4 Sealed off tube, demountable tube, mounting rings for phosphor samples and two CsI samples in plastic enclosure

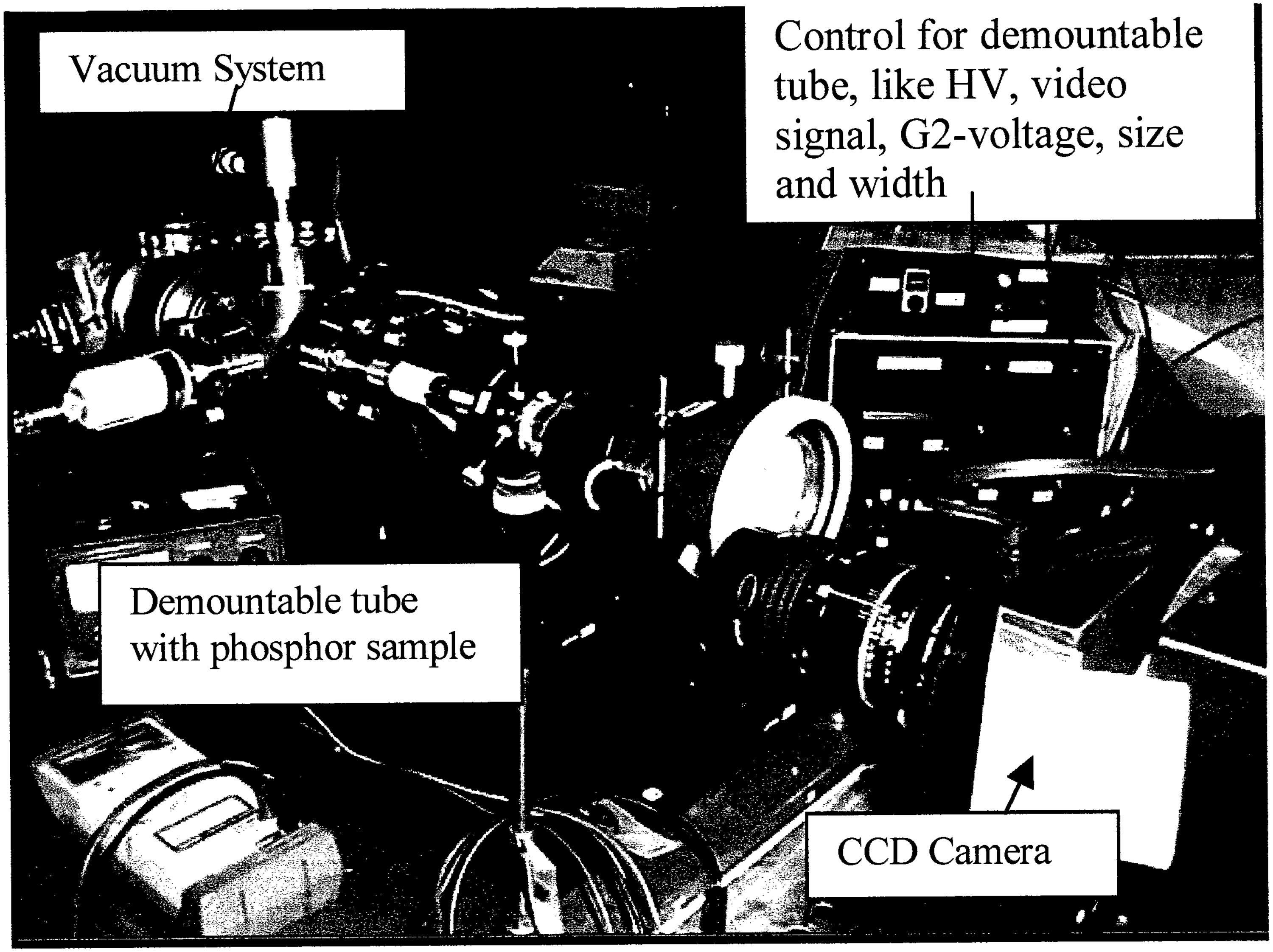

Fig. 5 Photograph of entire demountable system

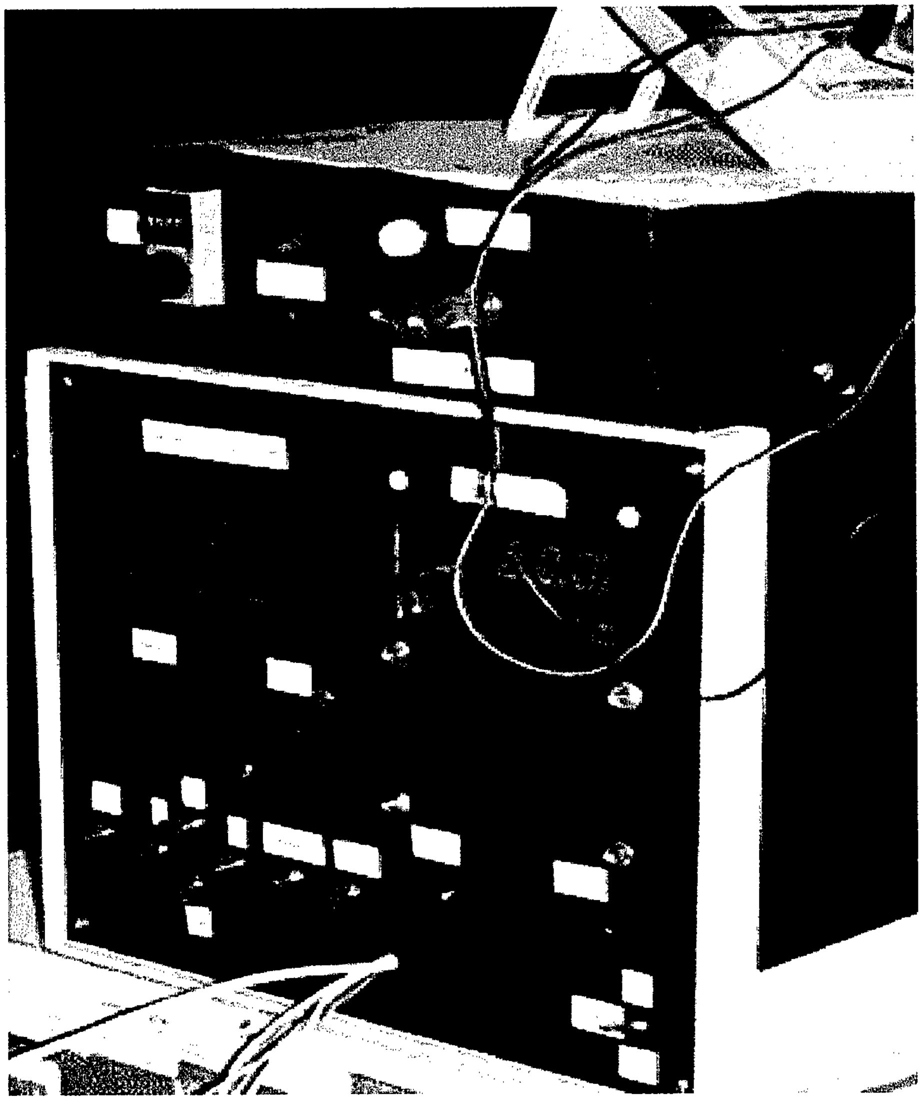

Fig. 6 The control box, providing tube voltages, video signals and meters to monitor current and voltages

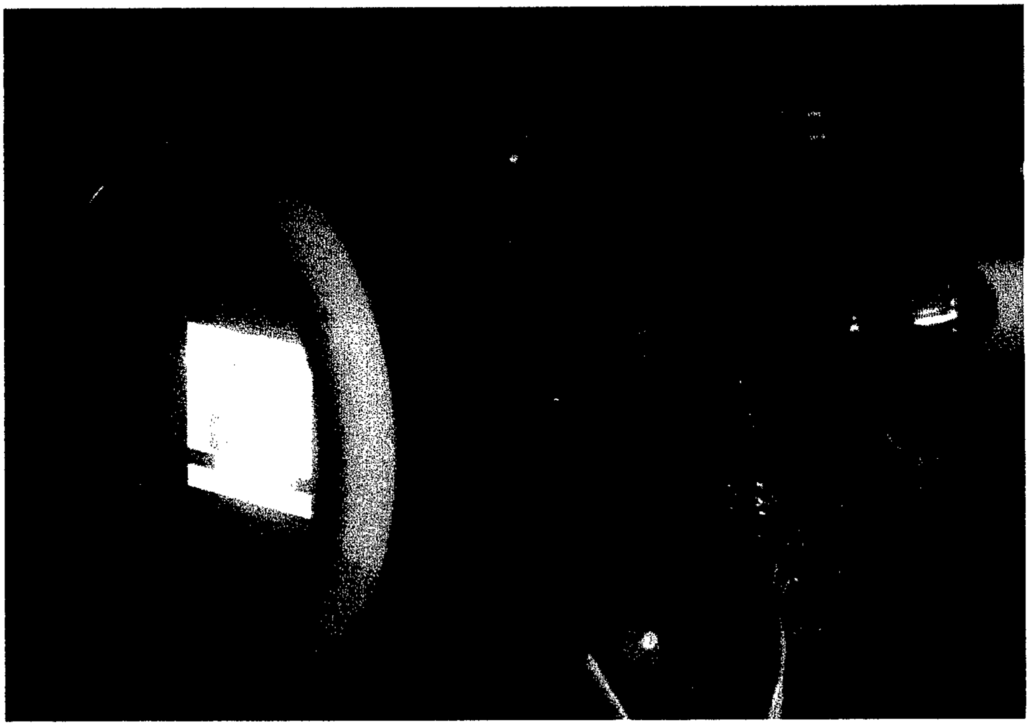

Fig. 7 Demountable display tube in operation. The sample used is one of the CsI samples.

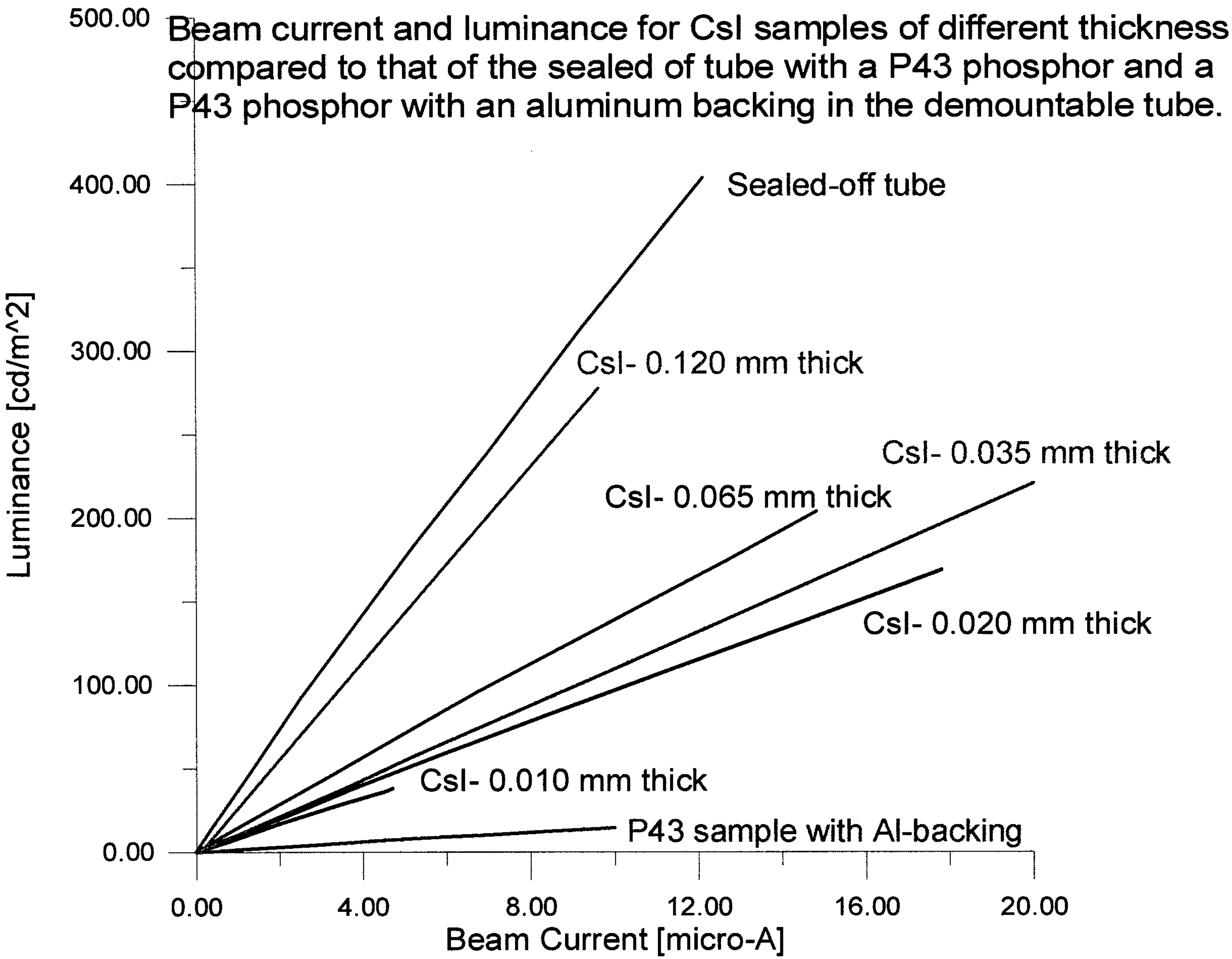

Fig. 8 Luminous response of CsI samples in comparison

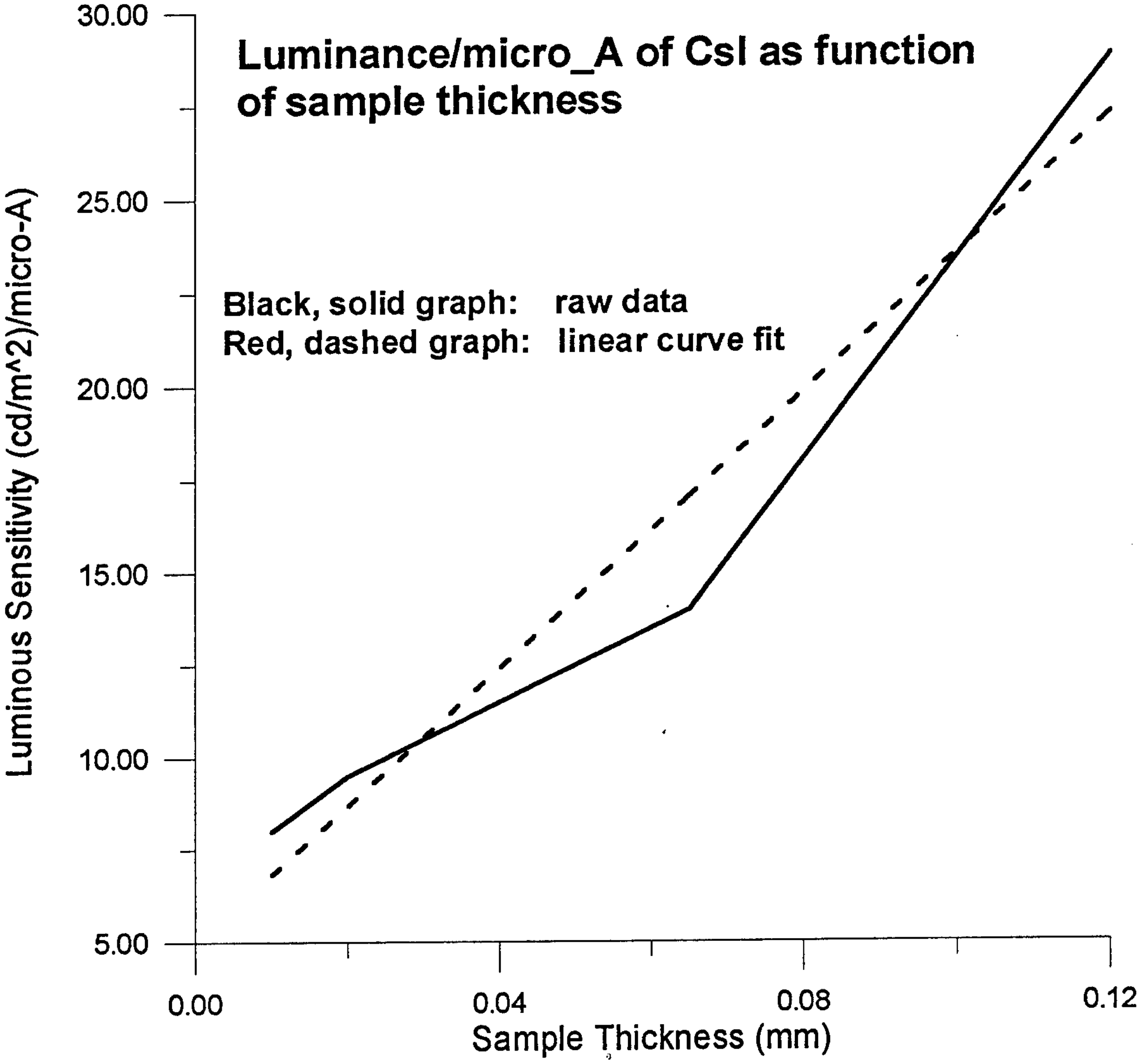

Fig. 9 Luminous response per unit current of CsI as function of sample thickness

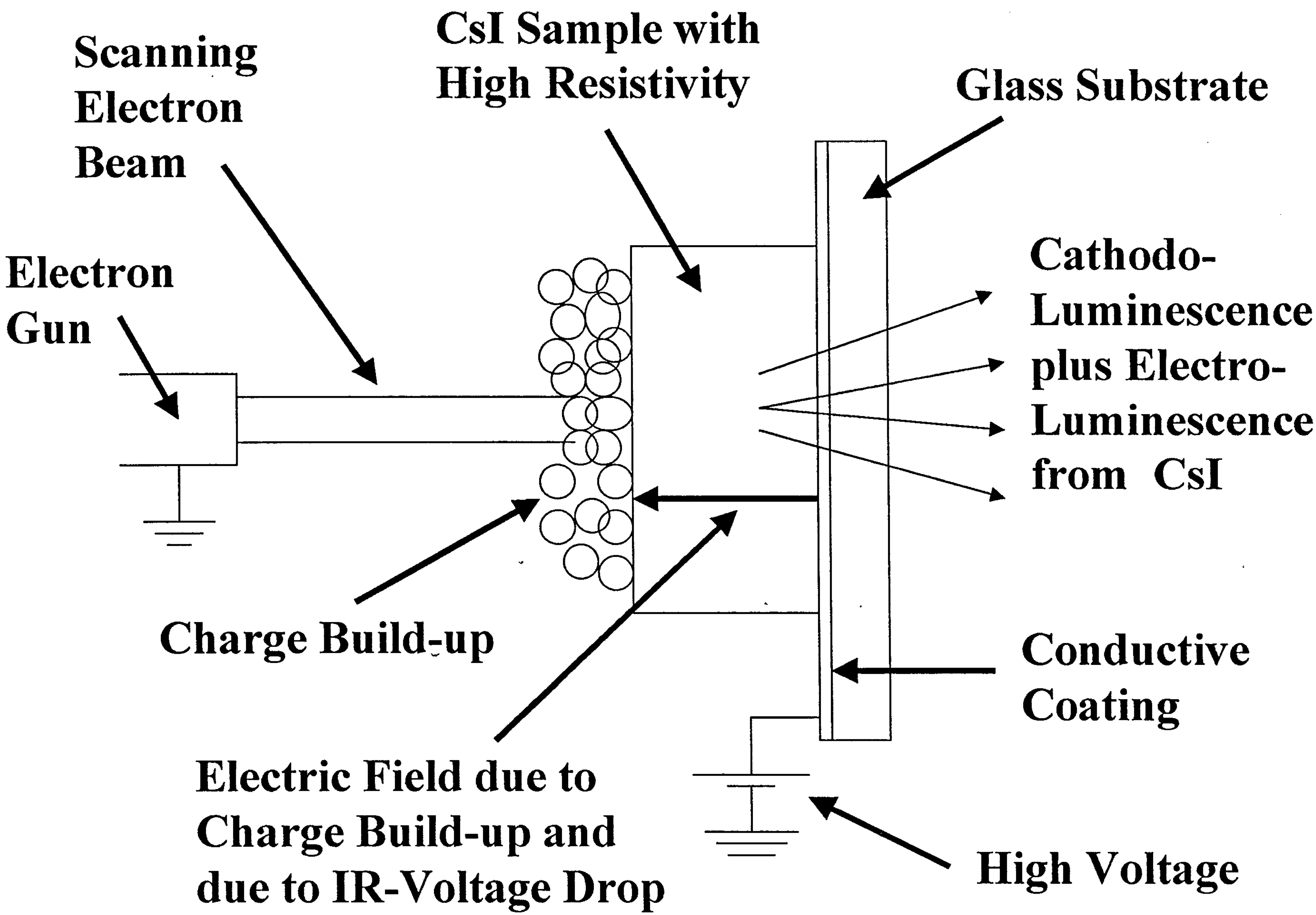

Fig.10. Model illustrating build-up of electric field in CsI to cause occurance of electro-luminescense in addition to cathodo-luminescense

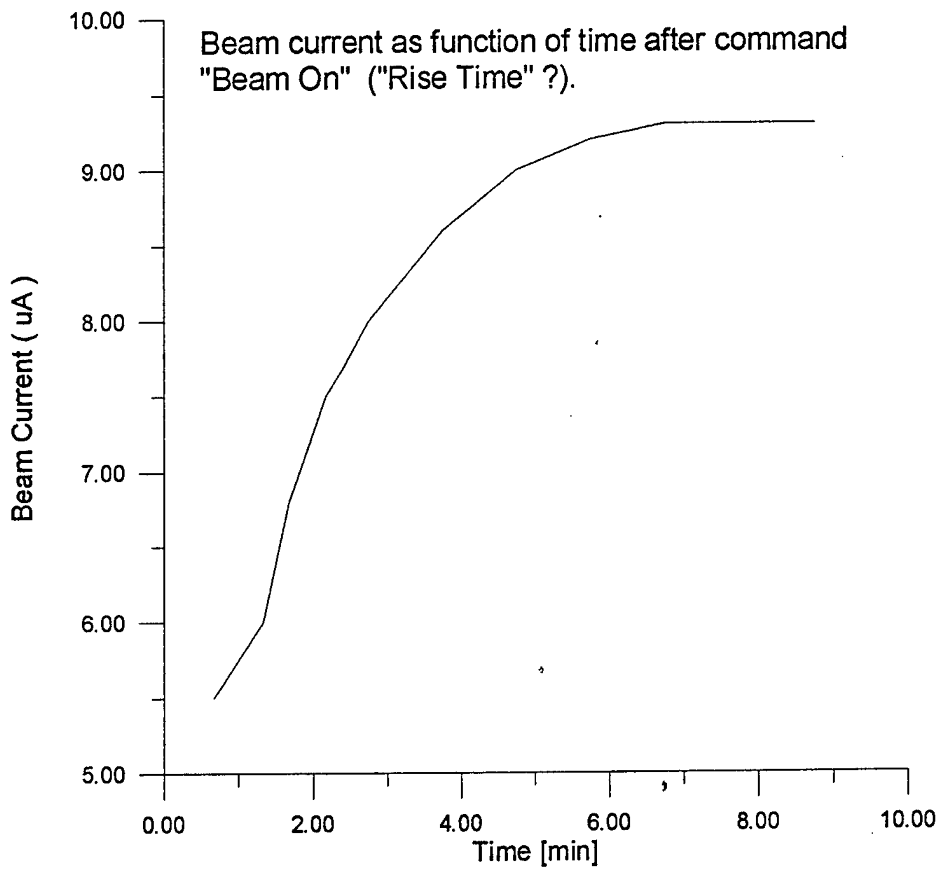

Fig. 11. Beam current as function of time after placing the command "Beam On".

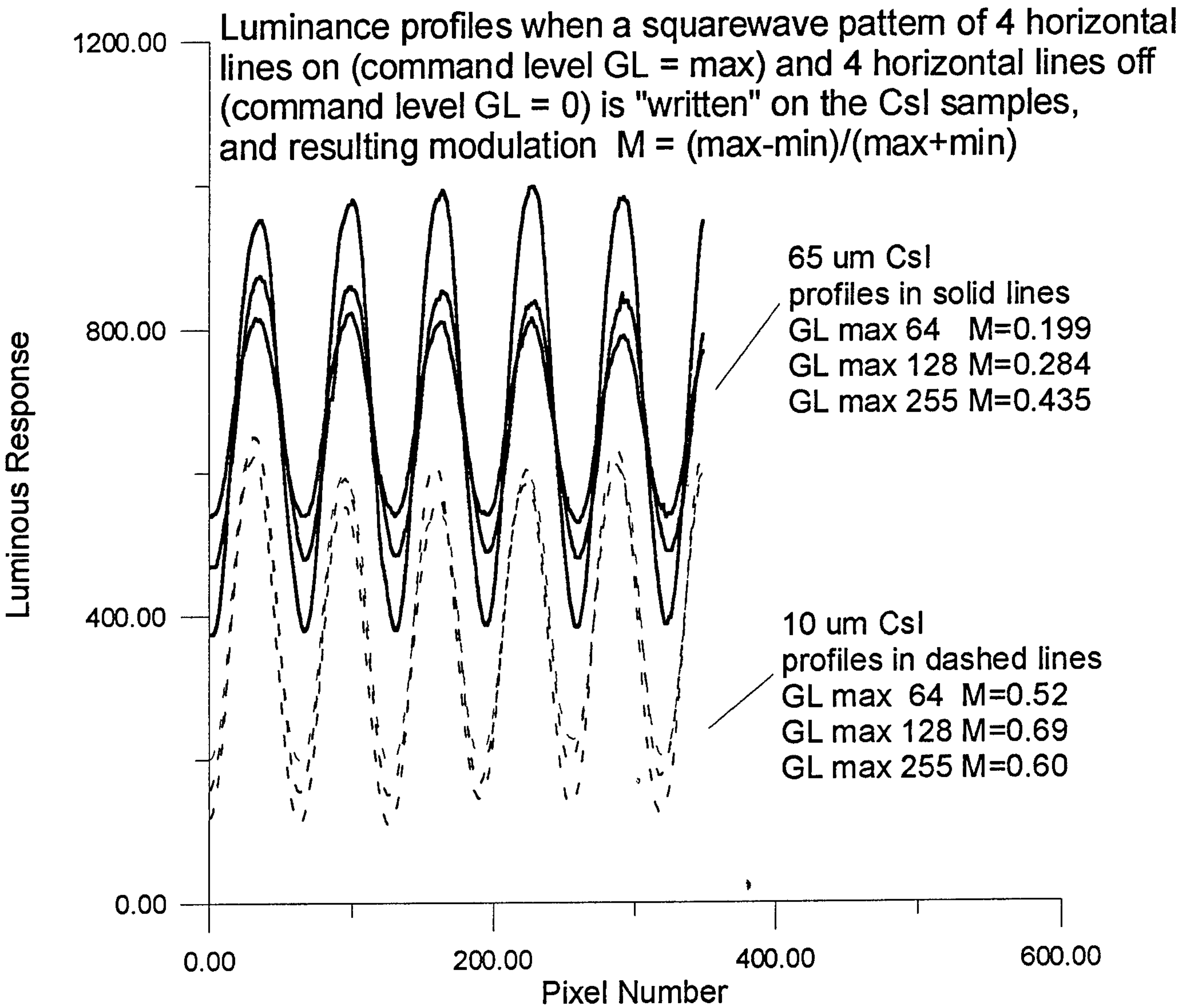

Fig. 12. Luminance profiles and output modulation for the for the 10 μm thick CsI Sample and for the 65 μm thick CsI sample when square wave patterns of 4 pixels on and 4 pixels off at 100 % modulation are written on to the CsI samples

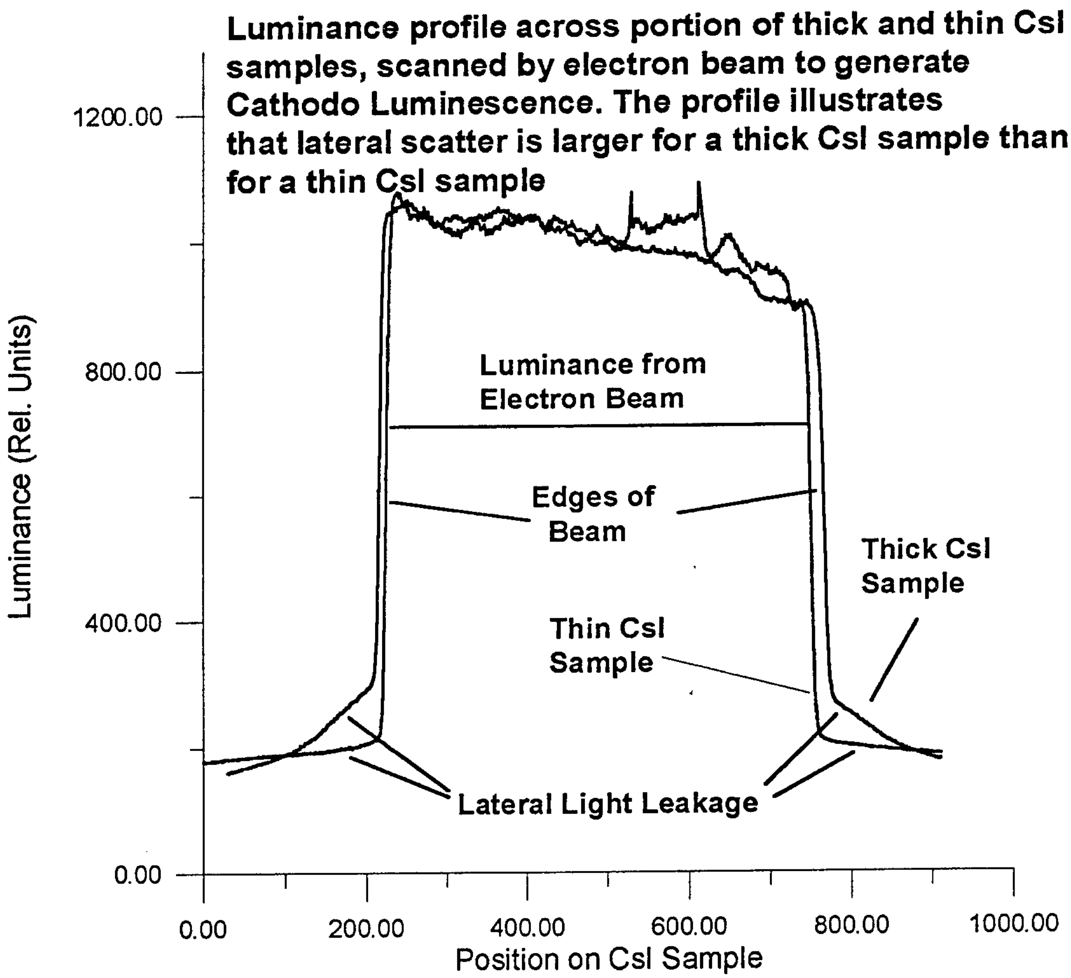

Fig. 13 Luminance profile across portion of CsI sample scanned by electron beam when a uniform image is displayed, illustrating lateral light scatter of CsI despite columnar growth.

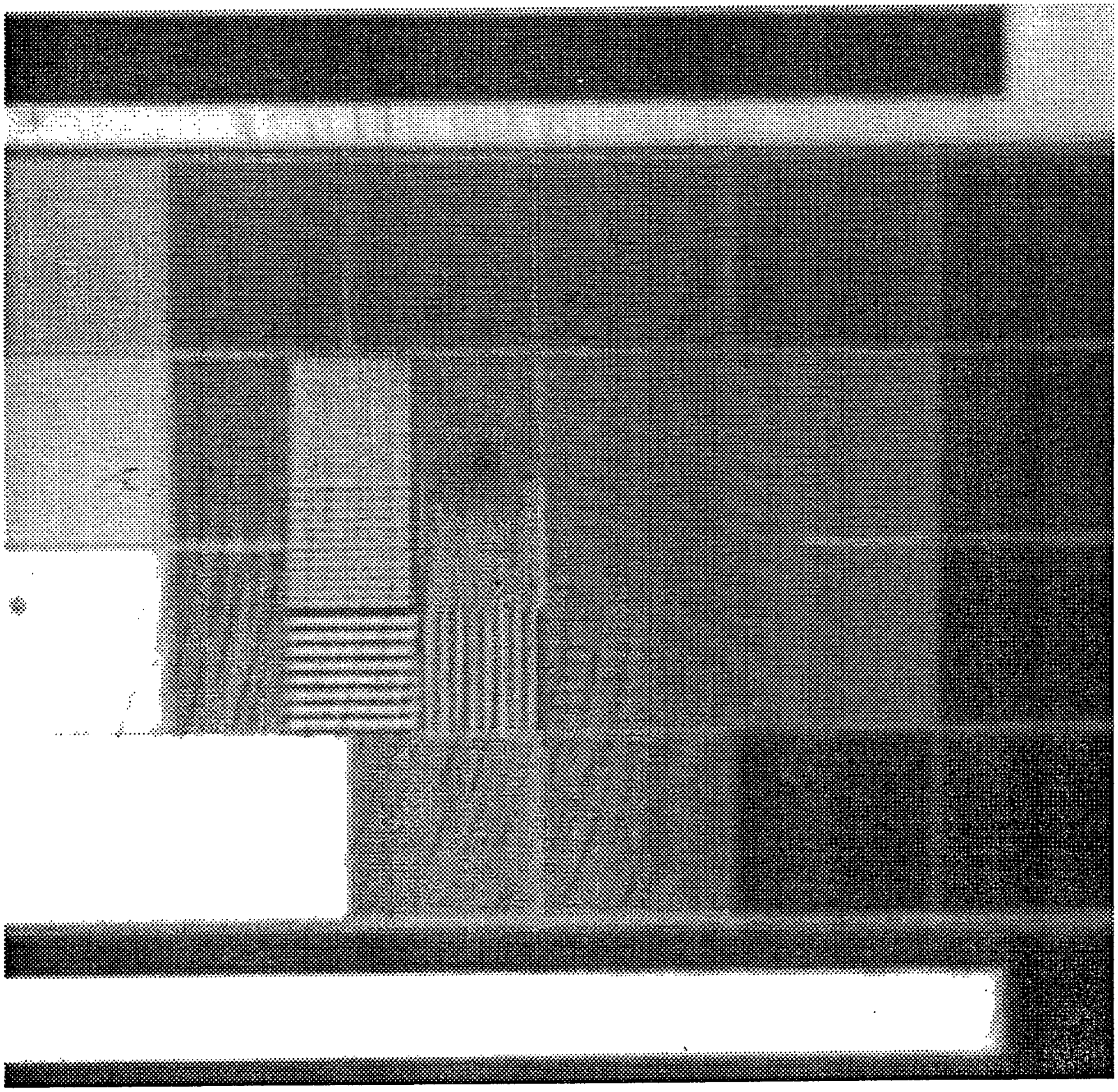

Fig. 14 CCD camera image of SMPTE pattern displayed by the 65 μm thick CsI sample in the demountable display tube